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Abstract

We validate through simulation and experiment that artificial magnetic conductors (AMC's) can be well characterized by a transmission line model. The theoretical bandwidth limit of the in-phase reflection can be expressed in terms of the effective RLC parameters from the surface patch and the properties of the substrate. It is found that the existence of effective inductive components will reduce the in-phase reflection bandwidth of the AMC. Furthermore, we propose design strategies to optimize AMC structures with an in-phase reflection bandwidth closer to the theoretical limit.

Introduction

The evolution of modern wireless technology demands antennas with high gain, low profile, and broad bandwidth. Three ways to achieve high gain in patch antennas include the use of (1) a ground plate positioned a quarter wavelength away which limits the bandwidth and the size miniaturization; (2) an electromagnetic wave absorption material under the patch (Refs. 1 and 2) which wastes half of the electromagnetic (EM) wave energy; and (3) an artificial magnetic conductor (AMC) underneath the patch (Ref. 3).

An AMC, which is also known as a perfect magnetic conductor (PMC) and high impedance surface (HIS), is a device that is artificially designed with thickness usually much smaller than the EM wavelength. Among all the properties of AMCs, the reflection phase is the most interesting one. With a normal incident wave from air, the reflection phase of a perfect electric conductor (PEC) is 180°, whereas, for an AMC, the reflection phase can be between –90° and 90° (Ref. 3), resulting in in-phase reflection. As a result, unlike the PEC, the close proximity of an AMC to the patch will add the incident and reflected waves to significantly increase the gain and bandwidth, as well as reduce the overall antenna size. Recent research has been focusing on bandwidth enhancement. The AMC can be modeled as a parallel LC circuit, where the in-phase bandwidth is improved by increasing the permeability of the spacer layer (substrate) and the separation between the surface patch and the metal back plate (Refs. 4 to 7). However, due to Snoek's limit, low loss magnetic materials with high permeability at microwave frequency are scarce (Ref. 8). Further miniaturization is limited by the allowable substrate thickness. In addition, a model with a parallel LC circuit is not applicable in the mushroom structure without vias, in which in-phase reflection remains (Refs. 6 and 9). In this manuscript, using a transmission line (TL) model for structures without vias, we will show that the in-phase reflection bandwidth has a theoretical limit. We explain why most AMC's do not reach the theoretical bandwidth and will show a design procedure to enable us to approach the theoretical limit.

Simulation and Measurement Set Up

Four AMC samples with different structures are considered. The sample, labeled as AMC_Via, has a via at the center connecting the surface patch to the ground plate with structural parameters shown in Figure 1 of a = 8 mm, h = 1.57 mm, d = 0.4 mm, and g = 1 mm. The other three samples do not have vias (d = 0 mm) and are labeled as AMC_0.2, AMC_0.5, and AMC_1.0 with the number referring to the value of g in mm. The metal is copper with conductivity of 5.8×10^{7} S/m, and the substrate is made of dielectric material FR-4 with $\mu = 1$ and $\varepsilon = 4.4 - j0.088$.

The TL model for an AMC is shown in Figure 1(c). The series-connected RLC circuit is used to characterize the surface patch. A TL_S component is used to represent the existence of the substrate which includes the parameters of ε, μ, and thickness. The metal back plate is modeled as a shorted line.

HFSS software (Ref. 10) is used to obtain the S-parameters of the structure involving the surface patch, via, and substrate, which are designated as the front components. With known ε, μ and the thickness of the substrate, the values of R, L, and C can be found by fitting the TL model shown in Figure 1(d) to the S-parameters of the front components (surface patch and substrate). To validate the TL model, we compare S-parameters (transmission and reflection) of the AMC front components with those of an HFSS simulation. The ideal situation arises when both results match throughout the frequency range of interest.

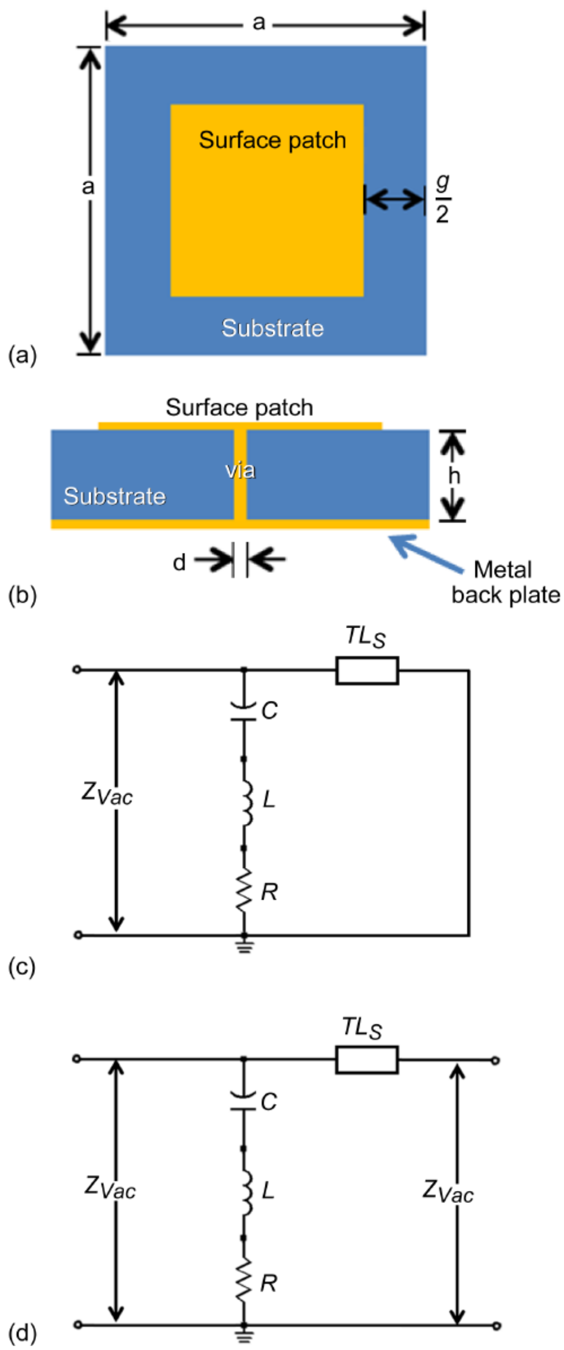

Figure 1.—Schematics and dimensions of the AMC structure in both (a) top view and (b) side view. The TL model of (c) an AMC structure, and (d) the surface patch for achieving the RLC circuit by fitting.

In HFSS simulations, only one unit is used. Several pairs of master and slave boundaries are set on the lateral sides of the unit to mimic the infinite periodic distribution of the AMC units (Ref. 10). In studying the properties of the surface patch without the ground plate, two Floquet excitation ports are set on the front and back sides of the structure to obtain both reflection (S_{11}) and transmission (S_{21}). The distance between the port and the structure is as far as 20 mm to mimic the plane wave propagation condition. Only one Floquet excitation port is used since the reflection is the only parameter of interest.

In the experimental measurements, two antennas are connected to the Agilent 8712ES network analyzer and are positioned in front of the sample. The distance between the antenna and sample is larger than $2D^2/\lambda$ to produce the plane wave propagation condition, where D is the diameter of the smallest sphere containing the horn antenna and λ is the wavelength of the microwave. The reflection of the AMC sample is calculated by $R_{AMC} = S_{AMC}^{Meas}/S_{Metal}^{Meas}$, where S_{AMC}^{Meas} and S_{Metal}^{Meas} are the measured transmission between the two antennas when the AMC sample and a thick circular metal plate of area $A = \pi r^2$ are respectively located in front of the antennas.

Calculation and Measurement Result

Table I shows the extracted RLC parameters by fitting the S-parameter of the front component simulated using HFSS. The fitted results are excellent as shown in Figure 2. It should be pointed out that the LC resonance frequencies based on the parameters shown in Table I are higher than 100 GHz for all four structures. In the considered frequency range (2 to 10 GHz), the impedance of the AMC structure is dominated by the effective capacitive component C in the RLC group. For example, at 12 GHz, the impedance of the L and C components of the AMC_Via sample are j5.93 Ω and –j88.89 Ω, respectively. It is also interesting that the RLC parameters are very similar for AMC_1 and AMC_Via samples, which confirms that the function of the via in the structure may not be important to the in-phase reflection performance (Refs. 6 and 9).

TABLE I.—THE RLC PARAMETERS OF AMC SAMPLES OBTAINED BY FITTING THE S-PARAMETERS OF THE FRONT COMPONENT

	AMC_0.2	AMC_0.5	AMC_1	AMC_Via
R (Ohm)	1.3466	2.1094	3.5812	3.5574
L (10^{-9} H)	0.0182	0.0425	0.1027	0.0957
C (10^{-12} F)	0.3964	0.2725	0.1811	0.1817

Figure 3 shows the phase of the reflection obtained from the HFSS simulation (red circles) and the TL model (blue lines) of each AMC structure. The results from the TL model match well with the HFSS simulations, showing that the frequency of 0° reflection phase decreases with decreasing g. It can be

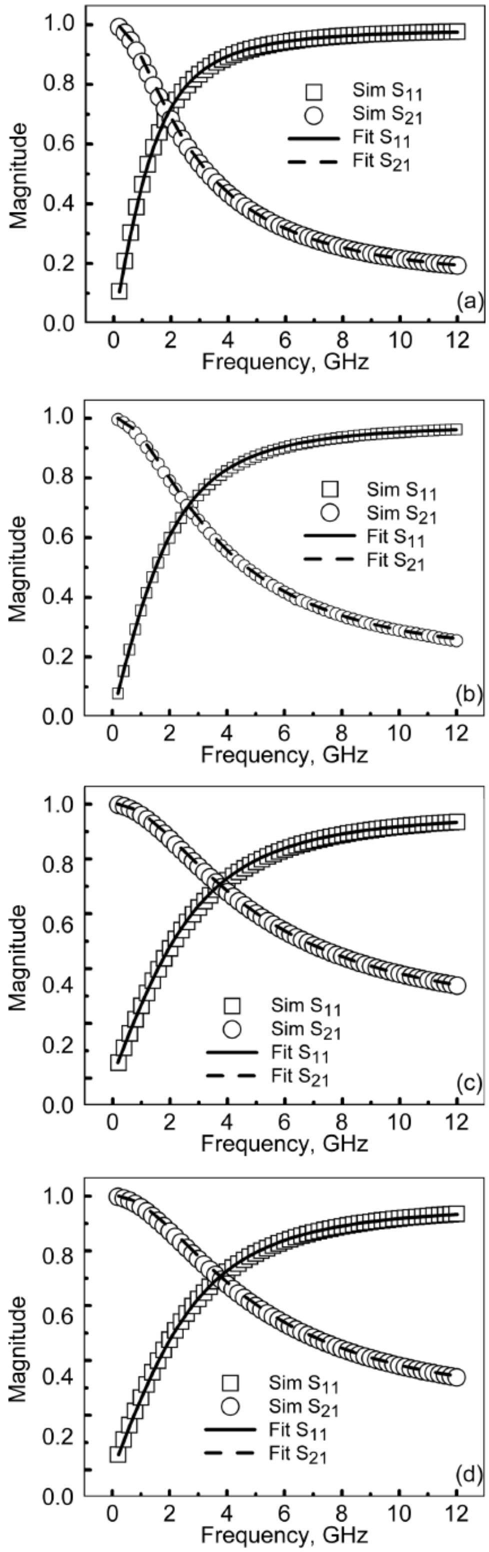

Figure 2.—S-parameters of the front components of the samples (a) AMC_0.2, (b) AMC_0.5, (c) AMC_1 and (d) AMC_Via from HFSS simulation (squares and circles) and calculated by using the extracted RLC parameters in Table I.

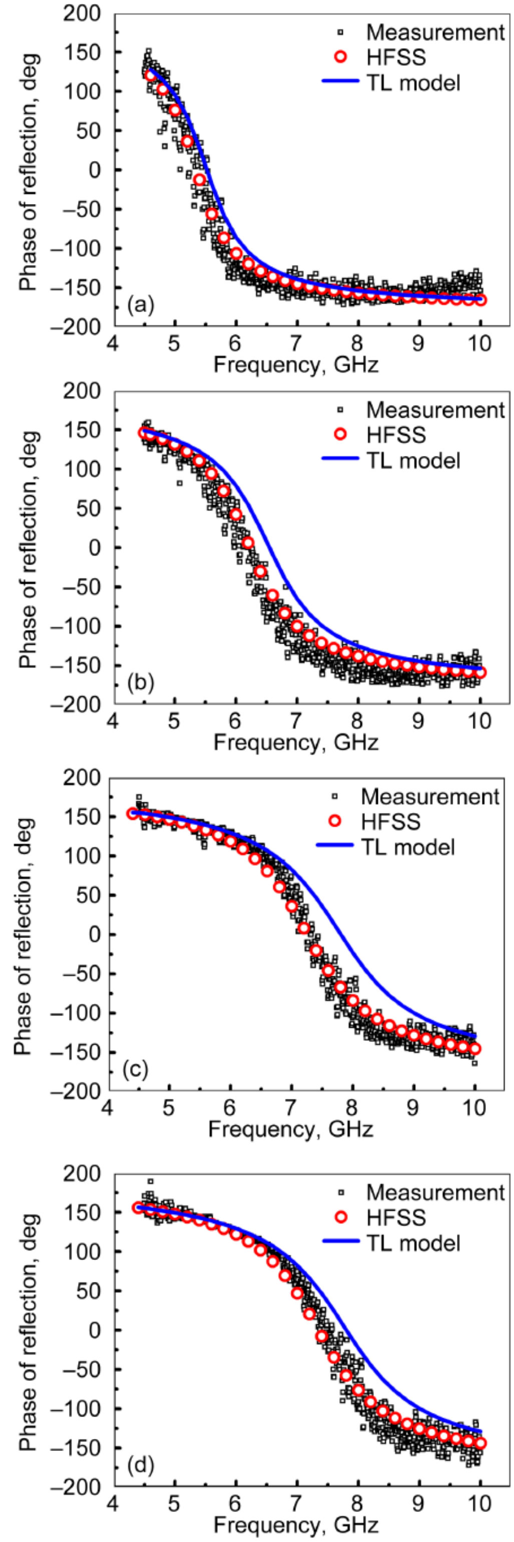

Figure 3.—The experimental data (black squares), and HFSS simulated results (red circles) and TL model calculated results (blue lines) of the samples (a) AMC_0.2, (b) AMC_0.5, (c) AMC_1 and (d) AMC_Via.

observed that the discrepancy between the model results and experiment increases as g increases. The RLC parameters of the surface patch are affected by the addition of the metal ground plate due to the change of the electric field distribution, which influences the C component. Samples with smaller g (closer patch) have less effect on the C component from the ground plate due to confinement of the electric field between the patches.

Figure 3 also shows the experimental measurement of the four AMC samples (black dots). In order to satisfy the infinite periodic boundary condition, each sample has a size of 190 by 203 mm, which is more than four times the wavelength of the electromagnetic wave in vacuum at the frequency with 0° phase reflection. Due to the limitation of the horn antenna working frequency, we are only able to measure the reflection from 4.5 to 10 GHz. It is clear that the experimental results agree very well with simulations for all samples. Since the TL model calculation is very similar to HFSS simulation and experimental results, it is reasonable to believe that the TL model will be able to characterize and quantitatively calculate the behavior of other AMC configurations.

Analysis of the TL Model

By analyzing the TL model in Figure 1(c), the existence of the L component of the surface patch will reduce the bandwidth of the in-phase reflection. Since we are only interested in the reflection phase behavior of the AMC structure, we assume a lossless AMC with a negligible inductive component and the thickness of the substrate is much smaller than the EM wavelength. Then the center frequency $f_{0,\mathrm{center}}$ and normalized bandwidth NBW_0 of the in-phase reflection in this baseline model can be derived to be:

$$f_{0,\ \mathrm{center}} = \frac{\sqrt{1+\left(\frac{4cCZ_0}{h\mu}\right)}}{4\pi C Z_0} \quad (1)$$

$$\mathrm{NBW}_0 = \frac{\mathrm{Bandwidth}}{f_{0,\ \mathrm{center}}} = \frac{2}{\sqrt{1+\left(\frac{4cCZ_0}{h\mu}\right)}} \quad (2)$$

Where c is the speed of light in vacuum, C is the capacitive component of the surface patch, Z_0 is the intrinsic impedance of vacuum, and h and μ are the thickness and the permeability of the substrate, respectively. Using a Taylor expansion to include the effect of a small but not negligible inductive component, the normalized bandwidth becomes

$$\mathrm{NBW}_\mathrm{L} = \mathrm{NBW}_0 - \frac{4c\left(h\mu + 3cCZ_0\right)}{Z_0\sqrt{h\mu}\left(h\mu + 4cCZ_0\right)^{3/2}}\mathrm{L} \quad (3)$$

Equation (3) shows how the inductive component in the transmission line affects the in-phase reflection bandwidth. Since the coefficient of L is negative, NBW_L will have the maximum value NBW_0 when L = 0. Furthermore, considering the property of the coefficient of L, three conclusions referring to the strategy of broadening the in-phase reflection bandwidth can be drawn:

1. The NBW of the AMC structures has a theoretical limitation which is expressed by Equation (2) using a thin substrate approximation.
2. Decreasing the inductive component L is an efficient way to push the NBW of an AMC closer to its theoretical limit.
3. Increasing the permeability of the substrate decreases the coefficient of L but enhances the L component. It is unclear that the use of a magnetic substrate will increase the NBW closer to the theoretical limit. However, it is certain that, according to Equation (3) the reduction of NBW caused by the existence of the inductive component can be minimized through increasing either the thickness of the substrate h or the capacitive component of the surface patch.

Conclusion

We have demonstrated in both HFSS simulation and experimental measurements that our TL model is able to describe the reflection phase behavior of AMC structures. A theoretical limit of the in-phase reflection bandwidth is derived using the TL model. The reduction of the in-phase reflection is caused by the existence of the inductive component of the surface patch, which can be minimized by using a thicker substrate or increasing the capacitive component of the surface patch.

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